Experimental search for the "LSND anomaly" with the ICARUS LAr-TPC detector in the CNGS beam

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Abstract

We report an early result from ICARUS (CNGS2), the large mass LAr-TPC, a "Gargamelle class" imaging detector of novel design. A search of a $\nu_\mu \to \nu_e$ signal due to a LSND anomaly at the Gran Sasso Laboratory, located at a distance of L = 730 km from CERN is hereby presented. Such an anomaly, in which an electron is produced by neutrinos in the energy interval

$0 \leq E_\nu \leq 30$ GeV, will be characterised by a fast energy oscillation averaging closely to $\sin^2\left(1.27\Delta m^2_{new}L/E_\nu\right) \approx 1/2$ and therefore approximately with probability $\left\langle P_{\nu_\mu \to \nu_e} \right\rangle = 1/2 \sin^2\left(2\theta_{new}\right)$. The presence of such a signal will be compared with the small but significant backgrounds due to other and more conventional neutrino origins.

The ionization information of the early part , before the showering of the e.m. track, has been examined wire by wire in order to tag the presence of an initial electron emitted from the vertex of the neutrino event, as a powerful eliminator of γ-converting pairs which are (1) generally separated from the vertex and (2) double minimum ionizing.

The Montecarlo (MC) emulations have been widely used in order to simulate the detection of real events, with an excellent agreement between MC and observed events. In order to simulate the LSND anomaly, MC electron events have been generated with the ν_μ CC energy spectrum. With the help of these MC events, the electron identification efficiency due to visibility cuts has been estimated and found to be $\eta = 0.74 \pm 0.05$.

The present ICARUS experimental sample has been based on 1091 neutrino events, about 50% of the ICARUS data already collected. Two events with a clear ν_e have been found, compared with the expectation of 3.7 events for conventional sources. Within the range of our observations, our result is compatible with the absence of a LSND anomaly. At 90% and 99% confidence levels, the limits are for 3.41 and 7.13 events with oscillation probabilities $\left\langle P_{\nu_\mu \to \nu_e} \right\rangle \leq 5.4 \times 10^{-3}$ and $\left\langle P_{\nu_\mu \to \nu_e} \right\rangle \leq 1.1 \times 10^{-2}$ respectively.

The present result strongly limits the window of opened options for the LSND anomaly, reducing the remaining effect to a narrow region centered around $\left(\Delta m^2, \sin^2\left(2\theta\right)\right) = (0.5\text{eV}^2, 0.05)$ where there is an over-all agreement (at 90 % CL) between the present ICARUS limit, the published limits of KARMEN and the published positive signals of LSND and MiniBooNE collaborations.

In order to complete the search of a signal due to a LSND-like anomaly especially in the hereby surviving $\left(\Delta m^2, \sin^2(2\theta)\right)$ region, we intend to move in the future the ICARUS detector to a much closer distance and to collect new data from a neutrino beam at lower energies

Neutrino oscillations have so far established a beautiful picture, consistent with the mixing of three physical neutrinos ν_e, ν_μ and ν_τ and mass eigenstates ν_1, ν_2 and ν_3. But it is possible that neutrinos are something very different than just a neutral counterpart of charged leptons, leaving room for additional neutrinos which do not see fully the ordinary electro-weak interactions but still introduce mixing oscillations with ordinary neutrinos. Indeed there are a number of "*anomalies*" which, provided they are confirmed experimentally, might be due to the presence of larger squared mass differences related to additional neutrino states with presumably some kind of "sterile" nature. Of course the astronomical importance of neutrinos in space is immense, so is their role in the cosmic evolution. A substantially heavier additional neutrino will be inevitably a source of the dark mass.

The possible presence of oscillations into sterile neutrinos has been proposed by B. Pontecorvo [1]. The experimental search for an anomalous production at short distances has been reported by the experiment LSND [2] at the Los Alamos 800 MeV proton accelerator with an anomalous excess of electrons from originated by muons from pions at rest with $< E_\nu > \approx$ 30 MeV and $L \approx 30$ metre. As well known, the LSND signal with anti-neutrino oscillations from such a small distance from the accelerator would imply an additional mass-squared difference largely in excess of the Standard Model values.

The LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal $\left\langle P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \right\rangle = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$ corresponds to an excess of $(87.9 \pm 22.4 \pm 6.0)$ events and it gives a 3.8 σ effect at L/E_ν distances of about $0.5 - 1.0$ metre/MeV The recent result from Mini-BooNe [3], performed with neutrinos from the 8 GeV FNAL-Booster, confirms a neutrino oscillation signal in the similar L/E_ν range at 3.8σ, present in both the neutrino and antineutrino channels.

Using the simple formula $\left\langle P_{\nu_\mu \rightarrow \nu_e} \right\rangle = \sin^2 (2\theta_{new}) \sin^2 (1.27\Delta m_{new}^2 L/E_\nu)$ one finds a very wide interval $\Delta m_{new}^2 \approx 0.01$ to 1.0 eV^2, depending on the actual and unknown value of $\sin^2 (2\theta_{new})$. Both experiments were based on a large volume of liquid scintillator whose light had been collected by photomultipliers. The purpose of the present analysis is to attempt a drastic reduction in the acceptable Δm_{new}^2 range.

In addition more recently an apparent *disappearance signal* of ν_e has been detected from (a) near-by nuclear reactors [5] and (b) from Mega-Curie k-capture calibration sources [6], originally developed for the Gallium experiments to detect solar ν_e. This signal is occurring for a Δm_{new}^2 largely in excess of the ones expected for ordinary neutrinos, maybe in the same order

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of magnitude of the LSND anomalies.

All these anomalies which have accumulated an impressive number of standard deviations, may indeed represent an unified approach in which the values of Δm^2_{new} may have a common origin, the different values of $\sin^2(2\theta_{new})$ for different channels reflecting the so far unknown structure of the $\mathbf{U}_{(j,k)}$ matrix, with k,j = the numbers of ordinary and sterile neutrinos.

The CNGS facility [7] delivers a neutrino beam essentially composed of muon neutrinos peaked in the range $10 \leq E_\nu \leq 30$ GeV, with an expected contamination from anti-neutrino at the level of 2% and an intrinsic electron component of slightly less than 1%. With the help of a novel development of a large mass Gargamelle class LAr-TPC imaging detector, the ICARUS experiment [8] is hereby searching visually the signature of $\nu_\mu \to \nu_e$ signal due to a LSND anomaly. The present experiment is at a much longer distance, L = 730 km, corresponding to a much larger $L/E_\nu \approx 36.5$ metre/MeV for a typical neutrino energy $E_\nu \approx 20$ GeV. An hypothetical $\nu_\mu \to \nu_e$ LSND/MiniBooNE anomaly will therefore produce very fast oscillations as a function of the neutrino energy E_ν, averaging closely to the value $\sin^2(1.27\Delta m^2_{new}L/E_\nu) \approx 1/2$ and therefore approximately with a signal $\langle P_{\nu_\mu \to \nu_e} \rangle = 1/2\sin^2(2\theta_{new})$. This signal will have to be compared with the small but significant backgrounds due to other and more conventional neutrino origins.

Bubble chambers have had a major role in neutrino physics: for instance the well known Gargamelle Freon bubble chamber, in spite of its relative small sensitive mass compared to other electronic calorimetric detectors of the times has contributed to the Standard Model with the discovery of the Neutral Currents and the visual observation of ν_e events.

LAr-TPC developed by the ICARUS group since about two decades [8] produces a completely uniform imaging with high accuracy of massive LAr volumes (up to about 700 ton), of density and interaction lengths comparable to the ones of heavy Freon. The new method observes the true "image" of the track with an accuracy of the order of few mm^3, thus extending to a liquid the TPC already described for a gas, originally proposed by G. Charpak et al. [9]. The passage from a gas to a liquid capable of several meters of free electron drift is not entirely trivial. A three orders of magnitude larger purity is necessary with equivalent Oxygen contents of the order of a few tens of ppt (parts per trillion).

Ionization tracks can be transported in ultra high purity LAr practically undistorted by a uniform electric field over macroscopic distances (meters). Imaging is provided by a suitable set of electrodes (wires) placed at the end of
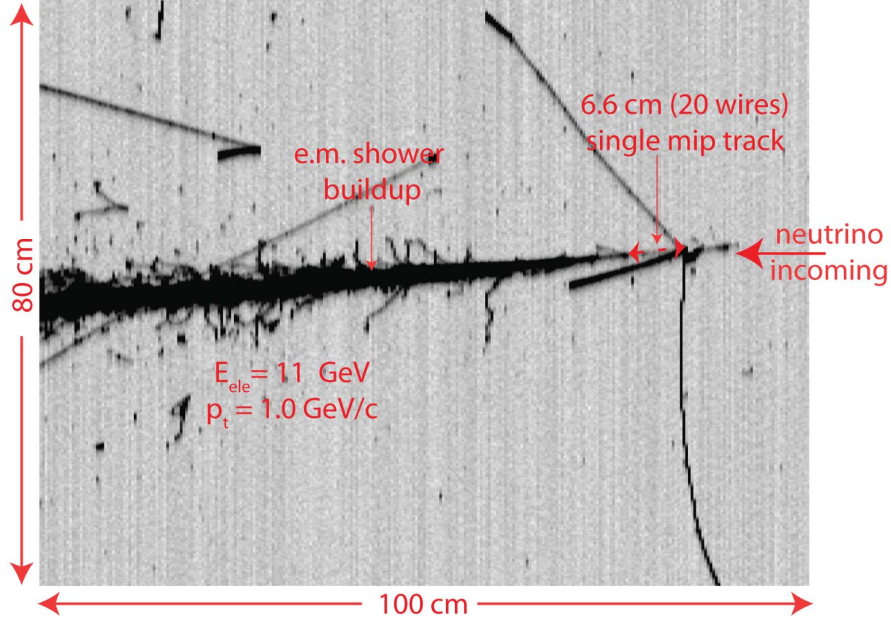
Figure 1: Typical Montecarlo generated event from the ICARUS full simulation programme [10] with $E_e = 11$ GeV and $p_T = 1.0$ GeV/c. In order to predict events with the LSND/MiniBooNE-like anomaly, a sample of ν_e CC MC events has been generated with the CNGS ν_μ CC energy spectrum. The close similarity of the MC simulation with actual ICARUS events (see Figure 2 (a) and (b)) is apparent.

the drift path continuously sensing and recording the signals induced by the drifting electrons. Non-destructive read-out of ionization electrons by charge induction allows detecting the entire signal of electrons crossing subsequent wire planes with different orientations. This provides simultaneously several projective views of the same event, hence allowing space point reconstruction and precise calorimetric measurement. A set of photomultipliers (PM's) is used in order to detect the prompt scintillation light simultaneously produced in the LAr. PM's are used in order to trigger the presence of the neutrino signal and to define the precise location of the information from the readout of the event.

These are important differences with respect to the previously reported observations of LSND and MiniBooNE which were based on the more primitive observation of Cerenkov rings recorded with PM's at the surface of the detector volume and mostly limited to quasi-elastic events and with a less immediate identification between gamma rays and electrons.
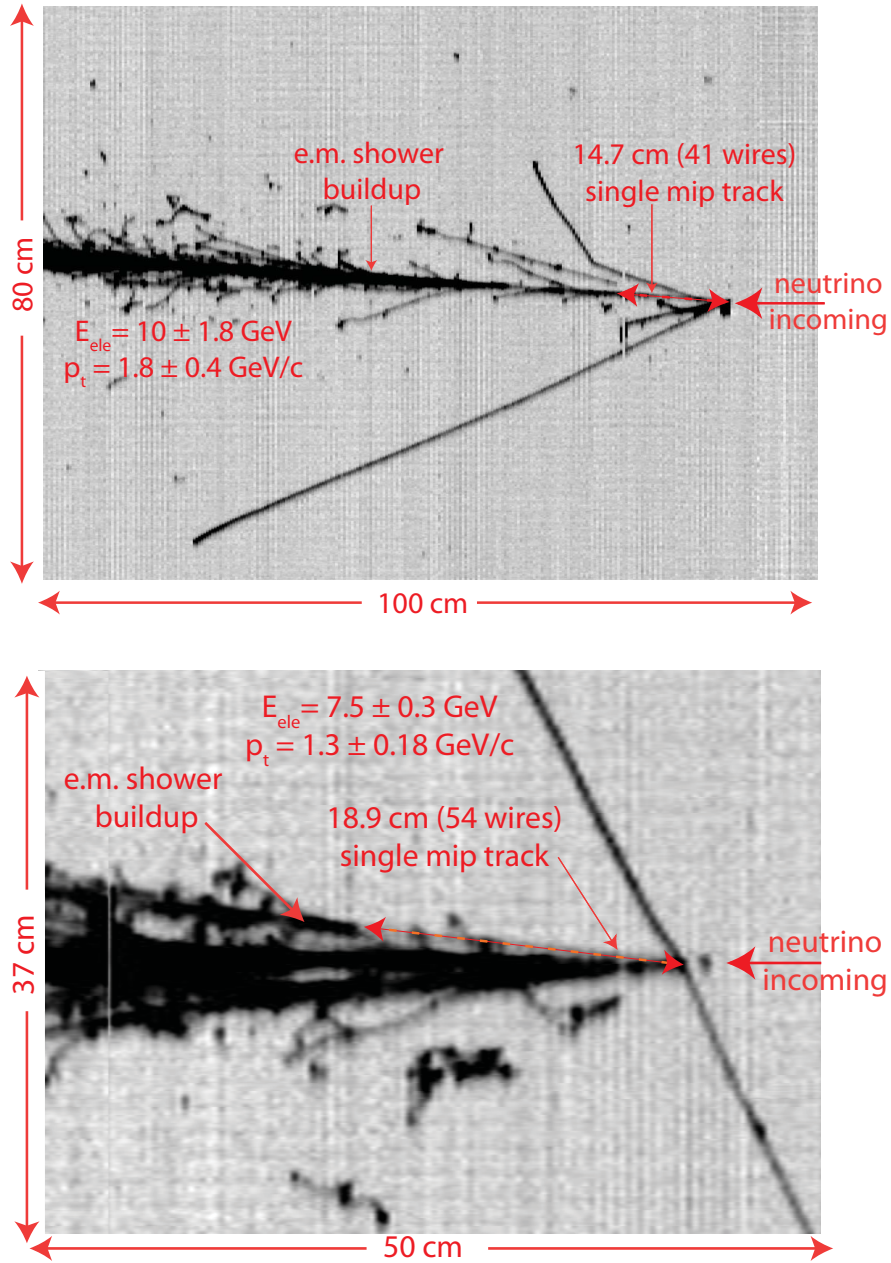
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Figure 2: Experimental picture of the two observed events (a) and (b) with a clearly indentified electron signature from a total sample of 1091 neutrino interactions. Event in (a) has a total energy of 11.5 ± 1.8 GeV, and a transverse electron momentum of 1.8 ± 0.4 GeV/c. Event in (b) has a visible energy of $\sim$17 GeV and a transverse momentum of 1.3 ± 0.18 GeV/c. In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event.

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The radiation length of LAr is 14 cm ($\approx$ 45 readout wires), corresponding to a γ-conversion length of 18 cm. The LAr-TPC detector allows identifying and measuring the ionization track by track, of all visible tracks produced in each contained neutrino interactions. The ionization information of the early part before the showering of the e.m. track has occurred, is examined wire by wire in order to tag the presence of an initial electron emitted by the neutrino event, as a powerful eliminator of γ-converting pairs which are generally separated from the vertex and generate double minimum ionizing tracks.

The detection of events has been widely simulated by a Montecarlo (MC) emulation [10]. The MC emulation is very sophisticated, reproducing in every detail the actual signals from the wire planes. Comparisons with the actual data samples are widely used to tune the reconstruction, check calibrations and optimize the identification and measurement algorithms. The agreement between MC and observed events has been excellent and it has been extensively used as a main guideline.

In order to predict events caused by a LSND anomaly, a sample of MC ν_e CC events has been generated with the CNGS - ν_μ CC energy spectrum. A simulated event is shown in Figure 1.

An "electron signature" has been defined by the following requirements: (a) fiducial volume for the vertex of the event, 5 cm distance from each side of the active volume and 50 cm distance from the exit plane; (b) the visible neutrino energy less than 40 GeV, in order to reduce the intrinsic beam induced background (c) the presence of a minimum ionizing relativistic electron track of sufficient length present from the vertex, subsequently building up into a shower; (d) clear separation from the presence of the other ionizing tracks near the vertex in at least one of the two transverse views ($\pm$ 60°), including short proton like recoils due to nuclear interactions. Out of an initial sample of 103 reconstructed events, 88 have a visible energy $E_{VIS} \leq 40$ GeV, of which 73 satisfy the fiducial volume cut. Visibility cuts reduce the identified electron tracks to 54 events corresponding to a selection efficiency $\eta = 54/73 = 0.74 \pm 0.05$. In a good approximation the value of η is independent of the shape of the energy spectrum. The present ICARUS experimental sample is based on 168 neutrino events (5.8×10^{18} pot) collected in 2010 and 923 events collected in 2011 (2.7×10^{19} pot out of the 4.4×10^{19} collected in 2011), leading to a total of 1091 initial neutrino events. In this sample only events with visible energy ≤ 30 GeV have been included with the relevant fiducial cuts, which bring the number of events from 1091 to 839.

We expect 627 - ν_μ CC , to which 204 ν NC and 3 ν_τ CC (except $\tau \to e$) are to be added.

The expected number of ν_e events due to conventional sources in the same energy range and fiducial volumes are as follows: (a) 3 events due to intrinsic ν_e beam associated contamination; (b) 1.3 ν_e events due to the presence of θ_{13} oscillations; (c) 0.7 ν_τ CC with $\tau \to e$ giving a total of 5 expected events. The expected visible signal is of 3.7 events after the $\eta = 0.74 \pm 0.05$ reduction has been applied due to visibility cuts coming from the general complexity of the events.

In the recorded experimental sample, two events with a clear ν_e have been identified (Figure 2), to be compared with the above expectation of 3.7 events for conventional sources.

Figure 2(a) has a total energy of 11.5$\pm$ 2.0 GeV, and an electron of 10 ± 1.8 GeV taking into account a partially missing component of the e.m. shower. Figure 2(b) has 17 GeV of visible energy and an electron of 7.5 $\pm$ 0.3 GeV. In both events the single electron shower in the transverse plane is clearly opposite to the remaining of the event, with transverse momenta for the electron of 1.8 ± 0.4 GeV/c and 1.3 ± 0.18 GeV/c respectively.

Within the range of our observations, our result is compatible with the absence of a LSND anomaly. Following Ref. [11], at statistical confidence levels of 90 % and 99% and taking into account the detection efficiency, the limits due to the LSND anomaly are respectively 3.41 and 7.13 events. Given the observed sample of 627 ν_μ CC events, the limits to the oscillation probability are 5.4×10^{-3} and 1.1×10^{-2} respectively. The exclusion area of the ICARUS experiment is shown in Figure 3 in terms of the two-dimensional plot of $\sin^2(2\theta_{new})$ and Δm^2_{new}. In most of the area covered by ICARUS and allowed by LSND and MiniBooNE the oscillation averages approximately to a half of its highest value, $\sin^2(1.27\Delta m^2_{new}L/E_\nu)$. At lower values of Δm^2_{new}, the longer baseline strongly enhances the oscillation probability with respect to the one of the short baseline experiments. In ICARUS and for instance with $(\Delta m^2, \sin^2(2\theta)) = (0.11 \text{ eV}^2, 0.10)$ as many as 30 $\nu_\mu \to \nu_e$ anomalous events should have been present with $E_\nu \le 30$ GeV.

The present result strongly limits the window of options from the Mini-BooNE experiment. Using a likelihood-ratio technique [3], CP conservation and the same oscillation probability for neutrinos and antineutrinos, a best MiniBooNE oscillation fit for 200 MeV $< E_\nu^{QE} <$ 3000 MeV has been given at $(\Delta m^2, \sin^2(2\theta)) = (0.037 \text{ eV}^2, 1.00)$. This is clearly excluded by the ICARUS result. A 3+2 joint oscillation fit as a function of E_ν^{QE} n
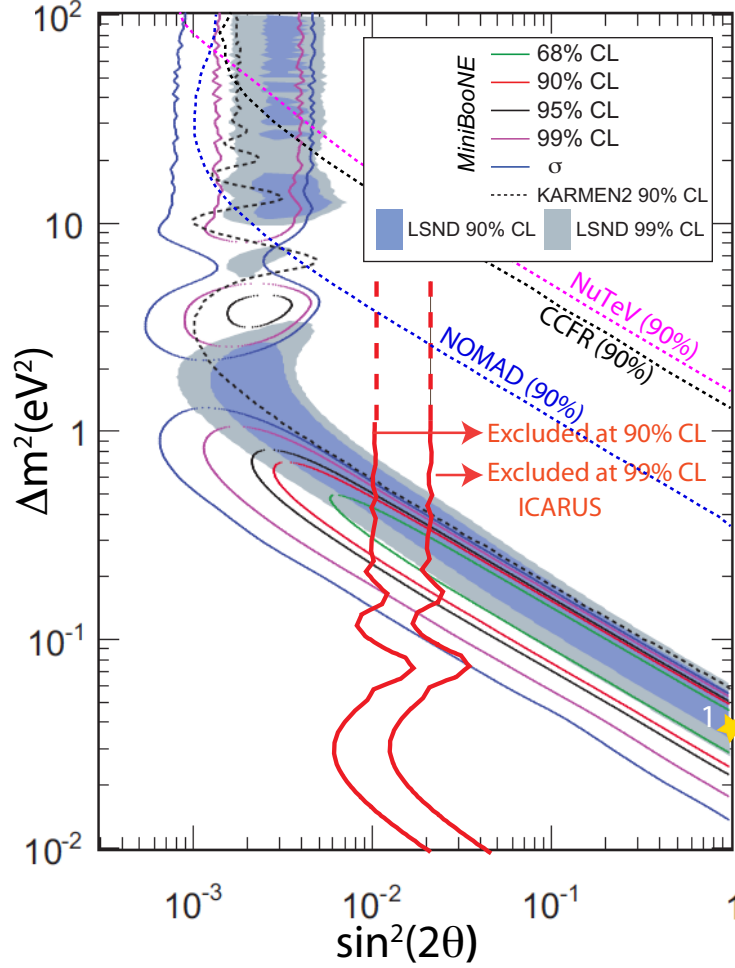
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Figure 3: Two-dimensional plot of Δm^2 vs $\sin^2(2\theta)$ for the main published experiments sensitive to the anomaly [2, 3, 4, 14] and the present ICARUS result. The ICARUS limits to the oscillation probability are 5.4×10^{-3} and 1.1×10^{-2}, corresponding to 3.41 and to 7.13 excess events respectively at 90% and 99% confidence level.

both neutrino and antineutrino modes has also been reported [3] with best fit values $\Delta m^2_{41} = 0.082$ eV^2, $\Delta m^2_{51} = 0.476$ eV^2, $\mathbf{U}_{e,4} = \mathbf{U}_{\mu,4} = 0.1844$, $\mathbf{U}_{e,5} = \mathbf{U}_{\mu,5} = 0.00547$, and $\phi = 1.0005\pi$. The MiniBooNE value is clearly incompatible with the present ICARUS result.

The oscillation probabilities from LSND are in the $L/E_\nu \leq 1$ metre/MeV region. The MiniBooNE result has extended the data to additional values

in the region $L/E_\nu > 1$ (Figure 4) and corresponding to a significant signal peak at smaller values of E_ν. The actual origin of the excess may need further clarification, as already pointed by the MiniBooNE Collaboration and for instance by Giunti and Laveder [12]. In the low mass peak region the dominant signal is due to ν_μ misidentified background adding to the observed LNSD signal.

As well known the present experiment explores much larger values of L/E_ν. But the ICARUS results exclude also a substantial fraction of the MiniBooNE $\left(\Delta m^2, \sin^2(2\theta)\right)$ curves shown in Figure 4, in particular the ones corresponding to the curves indicated with lines from 1 to 5.
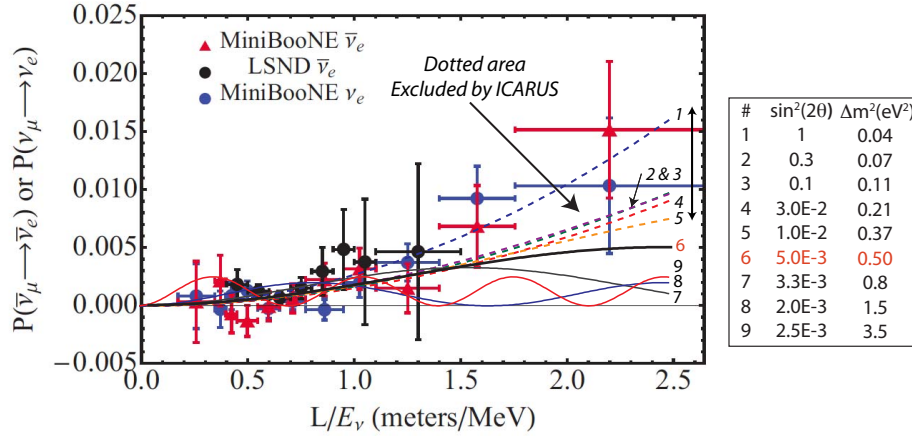

Figure 4: Observed values of the LSND and MiniBooNE results are given as a function of the distance . While there is general agreement at lower values of L/E_ν , the significant additional signal recorded by MiniBooNE for $L/E_\nu > 1$ metre/MeV is not entirely compatible with the ICARUS measurement when calculated at its much greater values of L. In particular lines indicated by 1-5 give a poor fit. Line 6 shows the "best value" with $\left(\Delta m^2, \sin^2(2\theta)\right) = (0.5 eV^2, 0.05)$.

A detailed comparison between the various results is shown in Figure 5. While for $\Delta m^2 >> 1$ eV^2 there is already disagreement between the allowable regions from the published experiments, for $\Delta m^2 \leq 1$ eV^2 the ICARUS result now allows to define a much smaller, narrower region centered around $\left(\Delta m^2, \sin^2(2\theta)\right)=$ (0.5 eV^2, 0.05) in which there is 90% CL agreement between (1) the present ICARUS limit, (2) the limits of KARMEN and (3) the positive signals of LSND and MiniBooNE collaborations. This is the area in which the expectations from cosmology suggest a substantial contribution to

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the dark mass signal.

This region will be better explored by the ICARUS/NESSiE proposed dual detector experiment [13] to be performed at CERN at a much shorter distances (300 m and 1.8 km) and lower neutrino energies, which increase the events rate, reduce the over-all multiplicity of the events, enlarge the angular range and therefore improve substantially the selection efficiency η.

Acknowledgements

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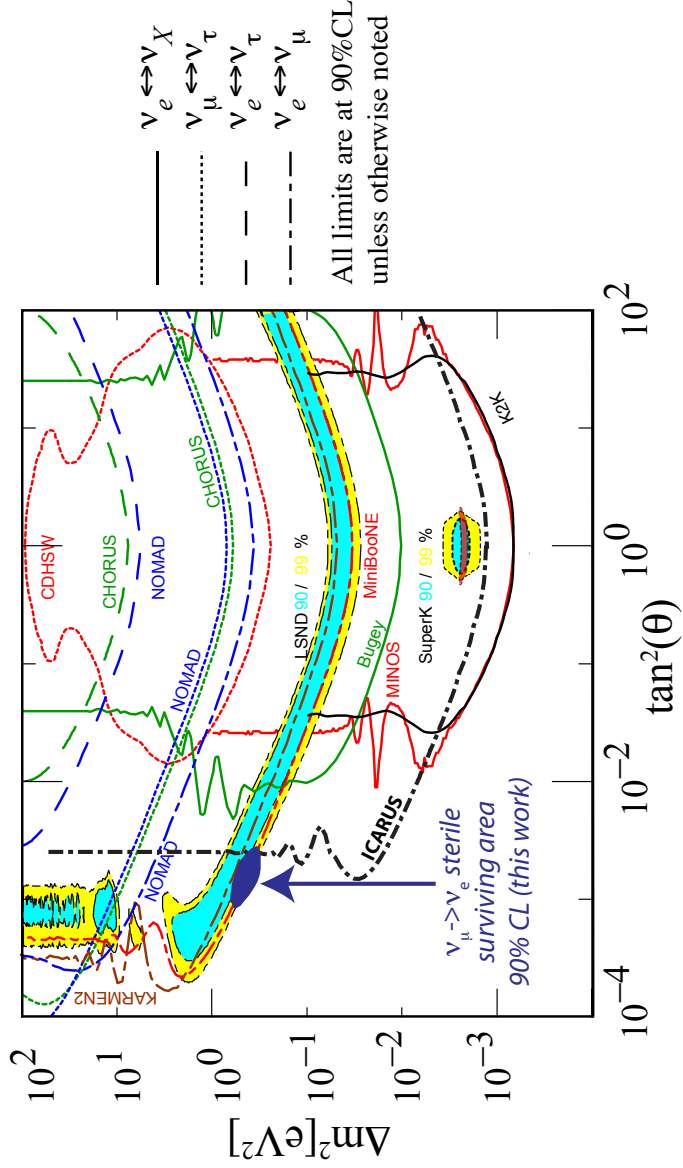
Figure 5: Regions in the $\left(\Delta m^2, \tan^2(\theta)\right)$ plane excluded by the ICARUS experiment compared with the published results (taken from http://www.pdg.org). While for $\Delta m^2 \gg 1eV^2$ there is already disagreement for $\nu_\mu \to \nu_e$ between the allowable regions from the published experiments, for $\Delta m^2 \leqslant 1eV^2$ the ICARUS result now allows to define a much smaller, narrower allowed region centered around $\left(\Delta m^2, \sin^2(2\theta)\right) = (0.5eV^2, 0.05)$ in which there is a 90% C.L. overall agreement.